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Technical Report

THE FLOW OF PLASMA IN THE SOLAR TERRESTRIAL ENVIRONMENT

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SPTP Accomplishments

In association with our NASA Theory Program, we have written 26 scientific papers and we have made 29 scientific presentations at both national and international meetings. Lists of the NASA Theory personnel, publications, and presentations are attached. Also attached is a brief description of how we spent the $120,000 provided by USU as a match to our NASA Theory Program.

Scientific Goals

It has been clearly established, both experimentally and theoretically, that the various regions of the solar-terrestrial system are *strongly coupled*, that the coupling processes exhibit *time delays*, and that *feedback mechanisms* exist. For example, changes in the solar wind dynamic pressure and the interplanetary magnetic field affect the magnetospheric currents and electric fields, which, in turn, affect the ionospheric convection pattern, electron density morphology, and ion composition at high latitudes. The changes in the ionosphere then affect the thermospheric structure, circulation and temperature on a global scale. The changes in the ionosphere-thermosphere system then act to modify the magnetospheric processes. The variations in the ionospheric conductivities modify the magnetospheric electric fields and the large-scale current system linking the two regions. Additional feedback mechanisms occur in the polar cap via the 'polar wind' and in the auroral zone via 'energetic ion outflow', and these ionospheric ions are a significant source of mass, momentum and energy for the magnetosphere. However, all of the coupling and feedback mechanisms have time delays associated with them, which further complicates the situation.

With the above description in mind, the overall goal of our NASA Theory Program is to study the *coupling, time delays,* and *feedback mechanisms* between the various regions of the solar-terrestrial system in a *self-consistent, quantitative,* manner. To accomplish this goal, it will eventually be necessary to have time-dependent macroscopic models of the different regions of the solar-terrestrial system and we are continually working toward this goal. However, our immediate emphasis is on the near-earth plasma environment, including the ionosphere, the plasmasphere, and the polar wind. In this area, we have developed *unique global models* that allows us to study the coupling between the different regions. These results are highlighted in the following subsections.

Another important aspect of our NASA Theory Program concerns the effect that localized 'structure' has on the macroscopic flow in the ionosphere, plasmasphere, thermosphere and polar wind. The localized structure can be created by structured magnetospheric inputs (i.e., structured plasma convection, particle precipitation or Birkeland current patterns) or time variations in these inputs due to storms and substorms. Also, some of the plasma flows that we predict with our macroscopic models may be unstable, and another one of our goals is to examine the stability of our predicted flows.

Because time-dependent three-dimensional numerical models of the solar-terrestrial environment generally require extensive computer resources, they are usually based on relatively simple mathematical formulations (i.e., simple MHD or hydrodynamic formulations). Therefore, another long-range goal of our NASA Theory Program is to study the conditions under which various mathematical formulations can be applied to specific solar-terrestrial regions. This may involve a detailed comparison of kinetic, semi-kinetic, and hydrodynamic predictions for a given polar wind scenario or it may involve the comparison of a small-scale particle-in-cell (PIC) simulation of a plasma expansion event with a similar macroscopic expansion event. The different mathematical formulations have different strengths and weaknesses and a careful comparison of model predictions for similar geophysical situations will provide insight into when the various models can be used with confidence.

Ionosphere – Magnetosphere Coupling → Electric Field Effects

Convection electric fields have a dramatic effect on the **E** and **F** regions of the ionosphere. As the ions drift through the neutrals, they are frictionally heated, which raises the ion temperature. The elevated T_i's then act to increase T_e and change the ion and electron densities because of temperature-dependent chemical reactions. In addition, the ion velocity distributions (O^+, NO^+, O_2^+, N_2^+) become non-Maxwellian in the regions of high electric fields. As the E-field increases, the ion distribution evolves from a drifting Maxwellian, to a drifting bi-Maxwellian ($T_\perp > T_\parallel$), to a drifting toroidal distribution. Of course, the ionospheric changes then affect the thermosphere, and the modifications in the global thermospheric circulation produces dynamo electric fields at low latitudes that significantly affect the equatorial ionosphere.

We conducted several studies of the effect that electric fields have on the ionosphere. We used our global ionospheric model to study the universal time and IMF B_y dependence of the ionospheric polar hole (paper 9); we modelled a unique low-density feature that exhibits a significant solar cycle dependence (paper 19); we modelled the ionosphere using a dynamic auroral oval based on Dynamics Explorer images (paper 12); and we compared the results obtained from our global ionospheric model with those obtained from the UCL-Sheffield coupled thermospheric-ionospheric model for very similar magnetospheric inputs (paper 14). We also studied the effect that dynamo electric fields have on the low-latitude ionosphere (papers 25 & 26). In addition, we wrote several topical review articles: one on 'Ionospheric Physics' for the IUGG (paper 7); one on the latest developments in the display of large-scale ionospheric and thermospheric data sets (paper 10); one on model studies of ionosphere/thermosphere coupling phenomena on both large and small spatial scales (paper 11); and one on the approaches that have been used for ionospheric modelling, simulation, and prediction (paper 15).

In the paragraphs that follow, we will only highlight two studies that are currently being conducted with our global ionospheric model. This model, which was developed with support from a previous NASA Theory grant, was the *first* numerical model of the *global ionosphere*. The model is a time-dependent, 3-dimensional, high-resolution, multi-ion ionospheric model that covers the altitude range from 90 – 1000 km. With the model, the density distribution of six ion species (NO^+, O_2^+, N_2^+, O^+, N^+, He^+) and the electron and ion temperatures are obtained from a numerical solution of the appropriate continuity, momentum and energy equations.

One of the ionospheric simulations we have just completed was for the major magnetic storm that occurred on 13 March 1989. During this storm, which persisted for more than 24 hours, the average $K_p \approx 8$, the cross polar cap potential was greater than 110 kV, and the auroral energy deposition was greater than 100 GW. As the storm developed, the plasma convection pattern expanded, convection speeds increased, and particle precipitation became more intense. These changes then affected the ion-neutral chemical reaction rates, the plasma transport coefficients, and the heating and cooling rates. The overall result was that there were major morphological changes in the ionospheric density and temperature distributions. The main plasma density trough moved equatorward of 50° magnetic latitude, the polar hole filled in, ion and electron temperature hot spots appeared, localized thermal anisotropies occurred, molecular ions dominated the F-region in certain places, and the height of the F-layer peak moved up to 500 km altitude on the dayside and down to 200 km on the nightside of the polar cap. We are currently writing a paper describing these results.

In another study, a total of 108 simulations of the high-latitude ionosphere were conducted for diurnally reproducible conditions. The simulations covered different solar cycle (high, medium, low solar activity), seasonal (winter, equinox, summer) and geomagnetic activity levels (high, moderate, low) for southward interplanetary magnetic field (IMF) conditions and B_y both positive and negative. Simulations were also conducted for both the northern and southern hemispheres allowing for the different displacements between the geomagnetic and geographic poles. The simulations show the presence of a number of high-latitude features, such as tongues of ionization, polar holes, auroral enhancements, the main trough, and ion temperature hot spots. The variations of these features with solar cycle, season, geomagnetic activity, universal time, and the IMF (convection and precipitation patterns) will be presented in a paper we are currently writing. A comparison of similar features in the northern and southern hemispheres will also be presented in this paper.

Ionosphere – Magnetosphere Coupling → Northward IMF

It is well known that the electric fields, particle precipitation, auroral conductivity enhancements, and Birkeland currents that couple the magnetosphere-ionosphere system are strongly dependent upon the direction of the IMF. When the IMF is southward, the Birkeland (or field-aligned) currents flow in the Region 1 & 2 current sheets, the *F*-region plasma convection exhibits a 2-cell structure with antisunward flow over the polar cap, the conductivity enhancements are confined to the statistical auroral oval, and the auroral electron precipitation is also confined to the classical oval. However, when the IMF is northward, the situation is considerably more complicated and less clear. In this case, an additional field-aligned current system occurs in the polar cap called the NBZ currents; plasma convection can be sunward in the polar cap and the pattern can assume multi-cell, severely distorted two-cell or turbulent characteristics; and particle precipitation occurs in the polar cap that can be uniform, in the form of multiple sun-aligned arcs, or in a θ-aurora configuration.

We have been and are continuing to conduct several theoretical studies in an effort to elucidate the ionosphere-magnetosphere coupling processes during northward IMF. One of our efforts involves the use of our electrodynamic model to investigate the 'large-scale' field-aligned currents that exist in the polar cap during northward IMF (papers 13 & 24). With our electrodynamic model, we solve Ohm's law and the current continuity equation so as to obtain self-consistency between the ionospheric conductivity, field-aligned current, horizontal E-region current, and convection electric field. In one effort, we used the USU conductivity model and conducted a systematic study of the influence of the ionospheric conductance on the form of the field-aligned current associated with the Heppner-Maynard 'distorted two-cell' convection pattern (paper 13). Our modelling results indicated that, contrary to previous claims, the NBZ current can be associated with the distorted two-cell convection pattern for most of the ionospheric conductivity conditions. We found that the seasonal and auroral activity conditions significantly affect the ionospheric conductivity and that the conductivity variations can influence the basic features of the NBZ current system associated with the distorted two-cell convection pattern. Based on these results, we suggested that the field-aligned current system observed by the MAGSAT satellite might imply a distorted two-cell convection pattern, and that a four-cell pattern is most likely to occur when the IMF is due north or very close to the north.

In another study, we are focusing on the ionospheric modifications associated with polar cap arcs. In particular, the spatial and temporal characteristics of the high-latitude ionosphere are being examined for plasma flux tubes that convect through polar cap arc structures. We are using our global ionospheric model, a simplified polar cap convection pattern and a generalized polar cap arc (electric field and precipitation) structure. We are examining the relative change of Σ_P, Σ_H, T_e, T_i, N(O^+, O_2^+, NO^+) for various electric fields, precipitating fluxes, and characteristic energies associated with polar cap arcs. We are attempting to characterize the range of observable modifications of the ionosphere by polar cap arcs for a wide range of solar activities and seasons. By characterizing the range of observable modifications of the ionosphere, we may be able to ascertain the important causal mechanisms in real polar cap arcs that produce the observable signatures of enhanced ionization, airglow, and convection. These modifications have important consequences for arc electrodynamics and chemistry, which may determine whether an arc is maintained, enhanced, or fades.

In a parallel effort, we developed the *first* time-dependent model of a polar cap arc. With the model, the electrodynamics of the arc is treated self-consistently in the coupled ionosphere-magnetosphere system. The physical processes that occur in a given model run are as follows. A magnetospheric shear flow carried by an Alfven wave propagates toward the ionosphere, which is characterized by simple background conductivity and convection patterns. The downward propagating Alfven wave can be partially reflected from the ionosphere and can bounce back and forth between the ionosphere and magnetosphere. Meanwhile, the upward field-aligned current associated with the Alfven wave enhances the conductance in the ionosphere, and the conductance change can launch a secondary Alfven wave towards the magnetosphere. The entire process is transient, during which all parameters in the ionosphere change in time self-consistently and the polar cap arc develops. Due to the finite conductivity in the ionosphere, the Alfven wave in the coupled ionosphere-magnetosphere system is eventually damped, and the polar cap arc approaches an asymptotic state.

In an initial series of simulations, we found that the time constant for the formation of the polar cap arcs is around 10 minutes. We also found that an initial single-peak precipitation associated with a polar cap arc tends to split into multiple peaks and leads to a multiple structure of the polar cap arc. In addition, we found that strong downward field-aligned currents can develop near the intensive upward field-aligned currents and form a pair structure of the field-aligned current in the polar cap arcs. The model predicts the existence of plasma flow crossing the polar cap arcs, but the time constant of such a flow is much larger than that associated with the development of the polar cap arcs. Our results also show that when the polar cap arcs approach a steady state, almost all of the upward field-aligned currents are closed by local downward field-aligned currents, which forms a locally self-closed current system around the polar cap arcs.

Ionosphere – Magnetosphere Coupling → Polar Wind

The polar wind is an ambipolar outflow of thermal plasma from the terrestrial ionosphere at high latitudes. The outflow, which typically consists of H^+ and He^+, begins at about 800 km. As the ionospheric ions flow up and out of the topside ionosphere along diverging geomagnetic field lines they are accelerated and eventually become supersonic (above about 1300 km). As part of our NASA Theory Program, we are studying the stability of the polar wind, we are modelling the 3-dimensional structure of the polar wind, and we are developing more advanced time-dependent polar wind models. These efforts will be briefly described in the following paragraphs.

Although the classical polar wind has been studied for twenty years, all of the studies conducted to date were based on either steady state or time-dependent, one-dimensional models applied to a *single location.* However, with support from our previous NASA Theory Program, we constructed the *first* three-dimensional, time-dependent, multi-ion model of the global polar wind in order to study the temporal evolution of ion outflow during magnetic storms and substorms. The model covers the altitude range from 120 to 9000 km. At low altitudes (120 – 800 km), 3-dimensional distributions for the NO^+, O_2^+, N_2^+, N^+, and O^+ densities and the ion and electron temperatures are obtained from a numerical solution of the appropriate continuity, momentum and energy equations. At high altitudes (500 – 9000 km), the time-dependent, nonlinear, hydrodynamic equations for O^+ and H^+ are solved self-consistently with the ionospheric equations taking into account collisions, charge exchange chemical reactions, flux tube divergence, and ion temperature anisotropies. The model can describe supersonic ion outflow, shock formation, and ion energization during plasma expansion events. Currently, our global polar wind model is being used to study the temporal evolution and 3-D structure of the polar wind during a substorm for four geophysical conditions. The four geophysical cases cover solar maximum and minimum and the summer and winter solstices. For each case, 154 convecting flux tubes are being followed for latitudes poleward of 50° north and for a period of time that covers the pre- and post-substorm phases in addition to the substorm itself. Each trajectory takes about 10 CPU hours on our Stardent (5 CRAY-XMP hours), and for the 154 trajectories and 4 cases we need approximately 6100 CPU hours. Such a study would not be possible without a dedicated mini-supercomputer, which we obtained via USU matching funds to our NASA Theory grant. The study is important because we will not only obtain the temporal evolution of the 3-D polar wind during a substorm, but we will be able to calculate the 'global' polar wind outflow rate from the ionosphere to the magnetosphere, and hence, get a better estimate of the population of ionospheric H^+ ions in the magnetosphere.

In another effort, a graduate student (P.-L. Blelly) is developing more advanced, time-dependent polar wind models. In particular, he is using a flux-corrected-transport (FCT) numerical technique to solve *different sets* of generalized transport equations, including the Maxwellian based 8-moment, 10-moment, and 13-moment equations and the bi-Maxwellian based 16-moment equations. The latter sets have the advantage in that temperature anisotropies and collisionless heat flow effects are included. Currently, all four sets have been coded and simple time-dependent expansion scenarios are being considered to test the schemes. Eventually, the comparison of the different sets of transport equations for the same 'time-dependent' polar wind scenario will indicate what mathematical level is needed to properly describe the dynamic polar wind.

Another important aspect of the polar wind concerns the 'stability' of the flow. As the horizontally convecting ionosphere moves through the dayside cusp region, energetic ions are created at low altitudes, and subsequently, they overtake and penetrate the polar wind at high altitudes. These energetic ion beams passing through the polar wind could destabilize the flow, which would then affect the mass, momentum, and energy coupling between the ionosphere and magnetosphere. In an effort to address this issue, we conducted a systematic study of the effect of O^+ beams on the stability of the polar wind. The cases we considered covered a wide range of electron-to-background ion temperature ratios (0.1, 1, 10) and beam-to-background ion density ratios (0.1, 0.5, 0.9). We found that the polar wind is indeed unstable for a range of conditions. It tends to be more unstable for high electron temperatures and for nearly equal beam and background densities. Further details are given in paper 21.

Ionosphere – Plasmasphere Coupling

Although plasmaspheric dynamics has been studied for more than two decades, there are still several unresolved issues. The problems are not connected with the inner plasmasphere ($L < 4$), but with the plasmapause and the outer plasmasphere. One unresolved issue is concerned with the formation of the plasmapause, and another with the refilling of the outer plasmasphere following substorms. We have been and are continuing to pursue both of these important issues as part of our NASA Theory Program.

With support from a previous NASA Theory grant, we developed the *first* three-dimensional time-dependent model of the *global* plasmasphere in order to study ionosphere-plasmasphere coupling phenomena. The model solves the nonlinear hydrodynamic continuity and momentum equations along closed flux tubes for '*multiple H^+ streams*' arising from the conjugate hemispheres. This plasmaspheric model takes into account the production and loss of H^+, collisions of H^+ with O^+, and the motion of plasmaspheric flux tubes in response to convection electric fields (cross-L drifts). The model retains the inertial term in the momentum equation so that supersonic flow and various low frequency wave phenomena can be studied. This model is now being upgraded by a graduate student (L. Zhou) with support from our current NASA Theory Program. The upgrading effort involves the addition of dynamic O^+ and He^+ species, the inclusion of the ion and electron energy equations, the inclusion of the offset between the geomagnetic and geographic poles, and the addition of centripetal acceleration to the momentum equations. The improved model will then be used to study both the effect of cross-L drifts on plasmasphere refilling and the effect that substorms have on the formation of density structures at the plasmapause. This work will lead to a Ph.D. dissertation for L. Zhou.

Another graduate student, A. Khoyloo, is studying plasmasphere phenomena using a collisionless kinetic model, and this work will lead to his Ph.D. dissertation. The work he is pursuing is an outgrowth of a previous polar wind study that we conducted (Barakat and Schunk). In the polar wind study, we used a kinetic model to describe the interaction of the cold outflowing polar wind electrons with the hot precipitating magnetospheric electrons (polar rain), and we found that the hot/cold electron interaction could lead to a double layer electric field that acts to separate the hot and cold electron populations and energize the upflowing ionospheric ions. With funding from our current NASA Theory Program, A. Khoyloo is modifying the kinetic model so that it is applicable to closed plasmaspheric field lines. When the modifications are completed, he will study the interaction of the upflowing cold ionospheric plasma with the trapped hot ion and electron populations (ring current). The interaction may be similar to what was found for the polar wind, and if so, this would have important implications for plasmasphere refilling following geomagnetic substorms.

During the last year, we also published a paper on the 'plasmaspheric wind' (paper 17). The existence of this wind was originally suggested by Lemaire in 1985, but we expanded upon the original suggestion and provided additional experimental evidence in support of the hypothesis. The plasmaspheric wind is a slow (subsonic) expansion of the corotating plasma away from the Earth across geomagnetic field lines. This large-scale and continuous drift of cold plasma elements from the inner plasmasphere to the plasmapause and beyond is similar to the subsonic expansion of the inner solar corona. The slow plasmasphere expansion rate, which is governed by plasma interchange motion, is driven by an imbalance between pressure gradient, gravitational, centrifugal, and inertial forces. The expansion velocity is also controlled by the height-integrated Pedersen conductivity of the ionosphere. Based on the controlling mechanisms, we predict that the plasmaspheric wind should be reduced in the noon local time sector and enhanced throughout the night. We also predict that the plasmaspheric wind should be larger in the outer plasmasphere than in the inner plasmasphere. If our hypothesis about the plasmaspheric wind is correct, a very important loss mechanism for the plasmasphere has been neglected in all previous model studies.

Ionosphere – Thermosphere Coupling

In order to study the coupling, time delays, and feedback mechanisms between the ionosphere and thermosphere, we initiated the development of a time-dependent, three-dimensional model of the Earth's thermosphere so that we could eventually couple it to our global ionosphere and polar wind models. However, the model has been designed to complement, rather than compete with, the two global thermospheric general circulation models (TGCM) that are currently available. Specifically, there are two TGCM's available, including the NCAR model developed by R. G. Roble and the UCL model developed by D. Rees and T. J. Fuller-Rowell. Both the NCAR and UCL thermospheric models are time-dependent and fully global, but they are based on a uniform, fixed grid coordinate system. Typically, they are run with a fairly coarse spatial gird (5° x 5° for the NCAR model and 2° x 18° for the UCL model). Such a grid spacing is certainly adequate for global simulations, but may not be adequate for *detailed* studies of the thermospheric circulation near features such as the main trough and auroral oval. It also may not be adequate for northward IMF conditions, for which there is typically a considerable amount of structure in the polar cap.

Our thermospheric circulation model is based on a numerical solution of the continuity, momentum, and energy equations for a 'mean mass' neutral gas. The equations are solved in a spherical coordinate system fixed to the Earth over the altitude range from 97 to 500 km using a flux-corrected-transport (FCT) numerical technique. With use of our Stardent computer, we will be able to have a 0.5° grid spacing in the polar coordinate (latitude) and a 2° grid spacing in longitude. Currently, the coding for the basic model is complete and it is undergoing extensive tests using simple ionospheres and simple geophysical setups. In the near future, we intend to upgrade the heating and cooling rates, use more realistic geophysical conditions, and couple it to our global ionospheric model.

Solar Wind – Interplanetary Medium

We published four papers involving studies of the solar wind and interplanetary medium. One of the studies was motivated by the recent observations of interplanetary magnetic clouds and astrophysical jets (paper 20). In this study, we considered the evolution of a magnetized plasmoid, assuming that the plasmoid was initially in a magnetohydrostatic equilibrium. We found that if the finite relaxation time of the plasmoid is taken into account, excess magnetic potential energy may accumulate in the plasmoid during the expansion process. In another study (paper 4), a two-dimensional magnetohydrodynamic (MHD) model was used to calculate the latitudinal structure of the solar wind. The dynamical effects of the interplanetary magnetic field (IMF) were investigated and the results obtained were compared with the predictions of both 1-D and 2-D hydrodynamic models. We found that, contrary to the predictions of the hydrodynamic models, the MHD model predicts the existence of a proton density maximum at the magnetic neutral line whether or not there is a density maximum or minimum at the inner boundary (0.15 AU). The drift motion of the magnetic field lines toward the magnetic neutral line enhances the magnetic field strength around the neutral sheet, which may provide a possible explanation of the discrepancy between the measured IMF at 1 AU and that extrapolated from the photospheric magnetic field by the current source - surface modelling.

The other two studies involved the use of the bi-Maxwellian based 16-moment set of generalized transport equations (papers 1 & 3). In one study (paper 1), the 16-moment expression for the distribution function was used as an empirical formula to fit 'measured' solar wind distribution functions. We considered a wide range of measured proton distributions, including isotropic distributions, distributions for which only the core is isotropic, distributions elongated in the magnetic field direction, distributions with cores elongated in a direction perpendicular to **B** and with high-velocity tails parallel to **B**, and distributions with two peaks. We found that the 16-moment expression for the distribution can describe almost all of the measured proton distributions (~ 80%), which implies that the 16-moment transport theory should be able to properly describe the solar wind most of the time. In a follow-up study (paper 3), we obtained a numerical solution of the complete set of bi-Maxwellian-based 16-moment transport equations for the steady solar wind from 28

R_S to 1 AU. The proton densities, drift velocities, temperature anisotropies, heat flows, and distribution functions obtained at 1 AU are in agreement with the measurements, which again indicates that the generalized transport equations can successfully describe the 'steady state' solar wind.

Validity of Macroscopic Plasma Flow Models

Numerous mathematical formulations have been used over the years to describe plasma flows in the solar-terrestrial environment, including Monte Carlo, hybrid particle-in-cell (PIC), kinetic, semikinetic, hydromagnetic, generalized transport, and hydrodynamic formulations. All of these formulations have both strengths and limitations when applied to macroscopic plasma flows. For example, the transport formulations (hydromagnetic, generalized transport, and hydrodynamic) can describe multispecies flows, multistream flows, subsonic and supersonic flows, collision-dominated and collisionless regimes, chemically - reactive flows, and flows that are characterized by highly non-Maxwellian conditions (generalized transport equations). Typically, these formulations can also be extended to multi-dimensions. They are limited, however, in that they are obtained by truncating the infinite hierarchy of moment equations, and, in general, it is not clear how the truncation affects the solution. The kinetic and semikinetic models are particularly suited to collisionless, steady-state plasma flows. They have an advantage in that the full hierarchy of moment equations are implicit in the solution and multiple particle populations can be readily included. Some of their limitations are that they are difficult to apply to time-dependent, multi-dimensional or collisional flows, and, as a consequence of the latter, an artificial discontinuity can occur at the boundary. Monte Carlo and PIC techniques have the advantage that you follow the motion of individual particles and, hence, a lot of the important physics can be included self-consistently. Monte Carlo techniques are particularly useful for collision-dominated gases, and with the PIC approach, self-consistent electric fields can be easily taken into account. Some disadvantages are that both techniques are computationally demanding and, therefore, they cannot be easily extended to multi-dimensional situations. Also, when PIC techniques are applied to macroscopic flows, "macroparticles" are used, and this introduces numerical noise, which can significantly affect the resulting physics. Specifically, the random scattering of particles due to numerical noise can significantly reduce temperature and heat flow anisotropies in an artificial manner.

In an effort to more fully elucidate the validity of the various plasma flow formulations, we conducted a systematic comparison of several of the formulations for the same plasma flow conditions. We also attempted to elucidate some of the limitations associated with a given mathematical formulation so that the detrimental effects associated with the limitations can be minimized.

In one study (papers 6 & 16), we compared, in as consistent a manner as possible, solutions to the bi-Maxwellian-based 16-moment set of transport equations with those obtained from a semikinetic model, assuming boundary conditions characteristic of both supersonic and subsonic flows in the terrestrial polar wind as well as supersonic flow in the solar wind. For each case in which transport and semikinetic solutions were compared, three separate semikinetic solutions were generated. These three semikinetic solutions assumed the particle distribution function at the baropause to be an isotropic Maxwellian, a bi-Maxwellian, and a bi-Maxwellian based 16-moment expansion with zero stress, respectively. Our study demonstrated several important points: (1) For supersonic "collisionless" flows, the 16-moment transport theory and the semikinetic model assuming a 16-moment distribution at the baropause are almost identical in their predictions, even for the higher-order moments (parallel and perpendicular heat flows). This is true for both polar and solar wind conditions. (2) The semikinetic solutions assuming either a Maxwellian or a pure bi-Maxwellian at the baropause also show extremely close agreement with the transport results for the lower-order moments (density, drift velocity, and parallel and perpendicular temperatures), but are less accurate in their heat flow predictions. (3) The nearly precise agreement between the 16-moment transport solutions and the semikinetic solutions with a 16-moment distribution at the boundary, which implicitly contain the full hierarchy of moment equations, indicates that moments higher than heat flow (flow of parallel and perpendicular thermal energy) are not needed to describe the steady-state polar and solar wind cases considered in this study. (4) Because of its underlying assumptions, the semikinetic model is unable to properly describe subsonic H^+ flows. Therefore, a comparison of semikinetic and transport models for subsonic flow conditions must await future advances in the kinetic theory. (5) Collisions are clearly of importance in determining the thermal and heat flow structure of the solar wind. The 16-moment transport model, which incorporates the effects of Coulomb collisions, yields temperature anisotropies at 1 AU that are in agreement with measurements, while the semikinetic model, which is collisionless, does not.

In another study (paper 18), we focussed on the discontinuity that occurs in the particle distribution functions and their moments at the lower boundary of the collisionless regime when a kinetic or semikinetic model is used. This discontinuity appeared in all of the semikinetic models of the polar and solar winds published to date that included a diverging magnetic field configuration. Unfortunately, the discontinuity and the different approaches to remove it led to large 'quantitative' uncertainties in the calculated plasma characteristics. Our study of this problem indicated that the adoption of a Maxwellian velocity distribution at the boundary of the collisionless regime is inconsistent with the flow conditions for the case of a diverging magnetic field and this caused the discontinuity in all of the previous studies. We then noted that the discontinuity can be removed by adopting a 'non-Maxwellian' velocity distribution at the boundary, and we gave the necessary and sufficient condition this velocity distribution must satisfy in order to have a continuous semikinetic solution that is quantitatively correct. Although our results were specifically for the polar wind, our conclusions should also apply to other situations.

In another study (paper 8), a Monte Carlo simulation technique was used to model the flow of H^+ in the polar wind over an altitude range that included the collision-dominated region, the collisionless region, and the transition layer that separates the two regions. In the simulation, 10^6 test H^+ ions were monitored as they diffused across the system and the distribution function and associated moments (density, drift velocity, parallel and perpendicular temperatures, parallel and perpendicular heat flows) were calculated. We found that the flow changes from subsonic to supersonic near the transition layer and that the H^+ distribution becomes non-Maxwellian in the transition layer. It takes the form of a 'kidney bean' embedded in a Maxwellian. These Monte Carlo results are now being compared to those obtained from the generalized transport equations for the same polar wind scenario so that we can determine whether or not the generalized transport equations properly describe the plasma flow in the transition layer.

Plasma Expansion Phenomena

We have continued our studies of plasma expansion phenomena because of their relevance to certain solar-terrestrial flows (solar wind, polar wind, interhemispheric flow, etc.). The problem is that a rapid expansion of a plasma results in non-Maxwellian distribution functions, and consequently, superthermal tails, plasma instabilities, and wave-particle interactions may become important. Therefore, an understanding of the basic physics involved in a plasma expansion is necessary so that simplified, but reliable, macroscopic models can be developed for a range of solar-terrestrial applications.

In the past, we conducted *small-scale* numerical simulations in order to model plasma expansions *along* **B** using both 1-D (Vlasov - Poisson) and 2-D (PIC) codes. We also modelled *macroscopic* plasma expansions *along* **B** in order to compare the predictions obtained from the small-scale models with the macroscopic model. With support from our existing NASA Theory Program, we developed both a 2-D, height-integrated, cross-**B**, macroscopic plasma expansion model and a fully 3-D macroscopic plasma expansion model (papers 2, 5, and 22). Our 3-D model has a unique capability for handling the large parallel-to-perpendicular conductivity ratio that exists in the ionosphere and is fairly general in that it can describe a range of plasma expansion scenarios, including the expansion of preionized clouds, plasma clouds that evolve from neutral gasses, and plasma clouds that have 'initial' directional velocities at an angle to **B**.

Our 1-D, 2-D, and 3-D *macroscopic* plasma expansion models were run for similar expansion scenarios and the results were compared. The results were also compared to those obtained from the previous small-scale simulations. The comparison indicated that the *macroscopic* 1-D and 2-D models are indeed valid with regard to the expansion characteristics predicted by these models. The small-scale simulations predicted expansion features that were qualitatively similar to those obtained from the macroscopic simulations, but there were also important differences that resulted from the unrealistic size and simulation time of the small-scale simulations. This is an important result because, in general, one will not know when a feature predicted by a small-scale simulation is correct, and hence, the results from small-scale simulations cannot be accepted on face value. However, small-scale simulations are useful as a backup to a macroscopic simulation to test the stability of the flow conditions predicted by the macroscopic simulation.

Matching Funds

Utah State University has provided approximately $120,000 in matching funds to our NASA Theory Program. The bulk of the funds ($87,000) was spent the first year to purchase a Stardent computer. This computer has provided computational resources equivalent to approximately 10 CRAY-XMP *hours per day*. The Stardent also has a superb 3-D graphics package and a convenient movie-making capability. Since acquiring the Stardent, our Theory Group has had more than enough computational resources to conduct the studies outlined in our NASA proposal.

During the last year an additional $4,100 in matching funds was used to purchase a 1200 MB disk drive for the Stardent in order to enhance our storage capacity. Matching funds were also used to support a visiting scientist, Dr. J. Lemaire, who is a co-investigator on our NASA Theory proposal.

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SPTP Publications

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